UNIQUE WHITE DWARFS ACCOMPANYING RECYCLED PULSARS

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1. Introduction and Summary

Knowledge of the properties of the white-dwarf companions of radio pulsars can provide unique constraints on the characteristics and evolution of these binaries, as well as on those of its constituents. Many white-dwarf properties can be determined accurately from their spectra, but for the very faint pulsar companions spectroscopy has only become feasible with the advent of large telescopes like the Keck. Here, I introduce the two classes of pulsar, white-dwarf binaries, and describe for each what we have learned from a specific system, PSR J1012+5307 and PSR B0655+64, respectively, summarising what has been done (Van Kerkwijk & Kulkarni 1995; Van Kerkwijk, Bergeron, & Kulkarni 1996; hereafter Papers I & II), presenting new results, and discussing what the future may hold.

Briefly, for the companion of PSR J1012+5307 we find a DA spectrum, and infer a mass of $\sim 0.16~M_{\odot}$, the lowest among all spectroscopically identified white dwarfs. Combined with a radial-velocity orbit, a neutron-star mass between 1.5 and 3.2 M_{\odot} (95% confidence) is derived. The companion of PSR B0655+64 shows strong Swan C₂ bands, i.e., it is a DQ star. Unlike anything reported for other DQs, however, it shows variations in strength of the bands by a factor two. Most likely, the variations are periodic, with a period of ~ 9.7 h. This is substantially shorter than the 1 day orbital period, which can likely be understood in terms of its past evolution.

2. PSR J1012+5307

PSR J1012+5307 is a member of the largest group of binary pulsars, those with low-mass helium white dwarf companions. These systems have pre-

sumably descended from the low-mass X-ray binaries, in which mass is transferred onto a neutron star from a less massive companion. The mass transfer in these systems is stable and relatively well understood, and a number of predictions can be made (for a review of binary evolution involving neutron stars, see Bhattacharya & Van den Heuvel 1991). First, the neutron star will likely have accreted a substantial fraction, if not all, of the up to $0.7~M_{\odot}$ lost by the companion (e.g., Van den Heuvel & Bitzaraki 1995). Hence, one expects the neutron star to have increased substantially in mass, and to be spun up¹. For reasons not quite understood, the magnetic field seems to decay at the same time, perhaps by being quite literally buried (Romani 1990). If the neutron stars indeed have masses increased to $\gtrsim 2~M_{\odot}$ (assuming they started with the "canonical" 1.4 M_{\odot} ; for a recent census, see Van Kerkwijk et al. 1995), this would be very interesting, as it would strongly constrain the equation of state (EOS) at supra-nuclear densities (e.g., Cook, Shapiro, & Teukolsky 1994); for softer EOS, like the one recently proposed by Brown & Bethe (1994), such a massive neutron star would collapse into a black hole. The only system for which a neutronstar mass estimate is available, is PSR B1855+09, for which Kaspi, Taylor, & Ryba (1994) found $M_{\rm NS} = 1.50^{+0.26}_{-0.14}~M_{\odot}$ (68% confidence). As yet, the uncertainty is too high to allow one to draw a strong conclusion.

For the white dwarf, one predicts that it will have a helium core, since the companion never reached helium ignition. Furthermore, for the systems with orbital periods $\gtrsim 10$ d, there should be a relation between the orbital period and the white-dwarf mass (as a consequence of the core-mass, radius relation for giants; Refsdal & Weigert 1971; most recently for pulsar binaries, Rappaport et al. 1995), as well as a statistical relation between the orbital period and the eccentricity (Phinney 1992). The latter depends only on the assumption of having a Roche-lobe filling giant with a convective envelope at the end of the evolution, and has been confirmed (ibid.). The orbital-period, mass relation has only been verified at the short-period end, using (again) PSR B1855+09, for which Kaspi et al. (1994) determined an accurate companion mass from Shapiro delay in the pulse arrival times. At the long period end, we hope to obtain an additional constraint using PSR B0820+02, which has a DA companion (Paper I).

PSR J1012+5307 is a recently discovered 5.26 ms pulsar, which is in a 0.60 d orbit with a very low-mass companion (Nicastro et al. 1995). This system was deemed especially interesting as, given its small orbital period, it seemed possible to determine the radial-velocity amplitude and thus the mass ratio. Combined with the white-dwarf mass, this would give the mass of the neutron star.

¹These pulsars are called "recycled" because the spin-up process allows the radiopulsar mechanism to work again after the mass transfer ceases.

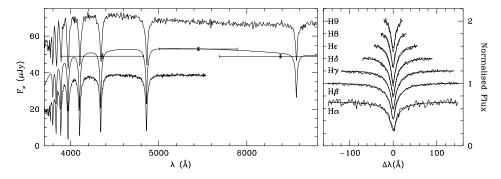


Figure 1. The spectrum of the white-dwarf companion of PSR J1012+5307 (taken from Paper II). Shown in the left-hand panel are a 10 Å resolution classification spectrum (top curve; offset by 15 μ Jy) and the average of eight 4 Å resolution spectra (bottom curve; offset by $-15 \mu Jy$). Also shown are the broad-band fluxes of Lorimer et al. (1995) and the best-fit pure Hydrogen model spectrum. The latter was derived from a fit to the profiles of H β up to H8, and has $T_{\rm eff}=8550\pm25~{\rm K}$ and $\log g=6.75\pm0.07.$ In the right-hand panel, the observed line profiles, including those of $H\alpha$ and H9, are shown with the modeled ones superposed.

Fortunately, the optical counterpart has V = 19.6 (Lorimer et al. (1995), making it the brightest pulsar companion currently known. Partly, it is so bright because it is relatively hot, with a colour-temperature of $T_{\rm BB} \simeq$ 9400 K. This indicates a cooling age of only a couple 10⁸ yr, much shorter than the pulsar spin-down age of 710⁹ yr. Since the pulsar presumably started spinning down at the time the white dwarf was formed, this is puzzling. It probably indicates that the pulsar did not start spinning at much shorter periods, as implicitly assumed in calculating the spin-down age, and as would have been thought based on simplistic models for the mass transfer. It could also be, however, that these low-mass white-dwarf have some residual hydrogen burning for quite a while after losing the redgiant envelope, and that the cooling-age estimate is wrong (Alberts et al. 1996).

We found that the companion was a DA star, showing H α up to H12 (Paper II; see Fig. 1). From a model-atmosphere fit (Fig. 1), we find $T_{\text{eff}} =$ 8550 ± 25 K and $\log g = 6.75 \pm 0.07$ (cgs units). To infer the mass, we need a mass-radius relation. Unfortunately, for these very low-mass helium white dwarfs, this is not well known. Using the Hamada-Salpeter zerotemperature relation, with an approximate finite-temperature correction based on models of Wood (1995), we find $M_{\rm WD} = 0.16 \pm 0.02~M_{\odot}$, the lowest among all spectroscopically identified white dwarfs.

We also measured radial velocities, and found a radial-velocity amplitude $K_{\rm WD} = 280 \pm 15 \text{ km s}^{-1}$, leading to a mass ratio $M_{\rm NS}/M_{\rm WD} =$ 13.3 ± 0.7 . Combined with the white-dwarf mass and the pulsar mass function, we infer that with 95% confidence $1.5 < M_{\rm NS}/M_{\odot} < 3.2$ (Paper II).

This determination is not yet accurate enough to constrain the equation of state, or to test evolutionary theory, but it does show that further study may well prove fruitful. It will be relatively straightforward to improve the accuracy of the radial-velocity amplitude and thus the mass ratio, which might already lead to an interesting constraint on the mass of the neutron star. It will be less easy to improve the estimate of the white-dwarf mass, because of the uncertainties in the mass-radius relation for these very low-mass white dwarfs, as well as the possible presence of helium in the atmosphere. If helium is present, the true surface gravity—and thus the inferred mass—will be lower (Bergeron, Wesemael, & Fontaine 1991; Reid 1996 for an observational indication).

The pulsar is relatively nearby and bright, however, and it may well be possible to derive an accurate distance using radio VLBI or timing. This would allow one to obtain a direct estimate of the radius. If this is the same as the predicted one $(0.028 \pm 0.002~R_{\odot})$, it would give confidence in the result. If it is not, one can either assume there is a problem with the mass-radius relation, but not with helium pollution, and infer a mass from the radius in combination with the observed surface gravity, or one can assume that there is helium pollution, but that the mass-radius relation is fine, and use that to derive a mass from the radius. Another possibility is to search carefully for Shapiro delay in the pulse arrival times, which would give a constraint on a combination of the white-dwarf mass and the inclination.

3. PSR B0655+64

The companion of PSR B0655+64 has a mass > 0.67 M_{\odot} (for a 1.4 M_{\odot} pulsar), and thus it must have been a relatively massive star. Most likely, the evolution has been similar to that leading to double neutron-star binaries like the Hulse-Taylor pulsar, with the system going through a phase as a wide high-mass X-ray binary, followed by spiral-in during a commonenvelope phase, leading to its current 1.03 d orbital period (e.g., Bhattacharya & Van den Heuvel 1991). Presumably, the helium core left was not massive enough to form a second neutron star. Since common-envelope evolution is rather poorly understood, there are few predictions for these systems, except that one expects a carbon-oxygen white dwarf. Most likely, it will have a helium atmosphere, since all the hydrogen left after the spiral-in will probably have disappeared during a second stage of mass transfer when the star became a helium giant (this is expected for low-mass helium stars; Paczynski 1971; Habets 1986).

The companion was identified by Kulkarni (1986). It has V = 22.2 and

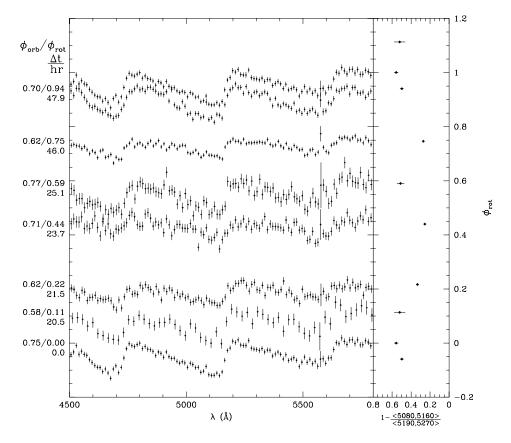


Figure 2. Spectra of the companion of PSR B0655+64. In the right-hand panel, a measure of the strength of the Swan bands is given. The numbers on the left indicate the time in hours since the first observation, the orbital phase, and the rotation phase for a period of 9.7 h.

V-R=0.1, indicating a temperature of about 6000 to 9000 K. First Keck spectra showed strong C₂ Swan bands (Paper I; see also Fig. 2), i.e., it is a DQ stars, with a helium atmosphere sufficiently shallow and convective to allow trace amounts of carbon to be dredged up (Pelletier et al. 1986).

Uniquely among DQ stars, a large variation in the strength of the Swan bands was observed, by about a factor two in less than two hours. In Paper I, this was interpreted as due to brighter and darker spots on the white-dwarf surface, possibly related to the presence of a magnetic fields (a locally higher magnetic field strength might lead to a change in gas pressure and thus temperature, or in convective efficiency). Based on the speed and amplitude of the variation, it was shown that if it was periodic, the period had to be ≥ 3 and ≤ 12 h. Thus, the modulation could not be orbital, but was most likely due to the white dwarf rotation. Spectra obtained in November 1995

confirm this (Fig. 2), and a period of 9.7 ± 0.1 h is indicated.

In Paper I, it was noted that if the star was rotating synchronously with the orbit when it was a Roche-lobe filling helium giant, it would have been spun up due to conservation of angular momentum when it shrunk to form a white dwarf. If the spin-up is mostly due to the angular momentum contained in the remaining giant envelope, the envelope mass must have been $\sim 10^{-4.5}~M_{\odot}$, interestingly similar to the typical helium-layer masses inferred for DQ stars (Pelletier et al. 1986; Weidemann & Koester 1995; Dehner & Kawaler 1995).

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